

Introduction to the Special Issue on the 2004 Sumatra–Andaman Earthquake and the Indian Ocean Tsunami

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The great Sumatra–Andaman earthquake of 26 December 2004 (UTC 00:58:53) was a momentous event, whether measured by scientific or human standards. Sadly, what is currently regarded as the third largest earthquake in recorded history led to the worst tsunami disaster in recorded history, with the loss of more than 200,000 lives and devastation throughout the Bay of Bengal. About three months later, on 28 March 2005, the Nias–Simeulue earthquake, near the southern end of the 2004 rupture, shocked the region again. Fortunately, this M_w 8.7 earthquake, the second largest earthquake in the past decade, was less destructive. These earthquakes and resulting tsunamis have been a sobering reminder to many in the community of earthquake scientists that the subject of our professional lives can have enormous impact on humanity. Hopefully, the legacy of the science presented in this volume will be a greater understanding of earthquake and tsunami processes that will be useful in advancing the resilience of our communities to Nature's violence.

The 2004 and 2005 earthquakes and tsunami revealed much that we did not know about great subduction zone events. Both the length of the 2004 rupture (perhaps as great as 1600 km) and its duration (upward of 600 sec) exceeded any previously recorded. Although the issue of whether the 2005 earthquake was an aftershock or triggered by the 2004 earthquake is currently debated, the 2005 earthquake was a significant event that may rank as one of the largest aftershocks ever recorded. The 2004 rupture extended through sections of the Sunda megathrust that had ruptured separately in earlier large earthquakes. The limited historical records and tectonic characteristics of this section of the megathrust had led many of us to believe that it was incapable of producing a giant earthquake. Nonetheless, such unanticipated natural events often lead to unanticipated advances in human knowledge. Fortunately, advances in geophysical instrumentation and field techniques made these the best-recorded great earthquakes and tsunami in history and set the stage for the work represented here.

The articles in this volume embody key aspects of the current state of knowledge about earthquakes and tsunamis. Topics include determinations of the spatial extent and evolution of the 2004 and 2005 ruptures from seismographic, geodetic, tsunami, and field observations, catalogs of pre-

vious and subsequent regional seismic activity, and evidence for previous tsunamis and deformation. Although the 2004 Sumatra–Andaman earthquake is the best-recorded great earthquake in history, its analysis posed many challenges, as many standard techniques proved inadequate to deal with such a giant event. Hence, this issue contains articles that present new techniques and unique datasets used and developed for this particular earthquake.

Earthquake Size and Energy

Size is a fundamental seismic parameter for any earthquake; using different datasets and techniques, the size of the 2004 Sumatra–Andaman event has been estimated within a range of values between M_w 9 and 9.3. The size of this earthquake is important for historical placement and for putting direct comparisons between this earthquake and the 1960 Chile event into context. Braitenberg and Zadro (2007) compare free oscillation amplitudes of both earthquakes as recorded by continuously recording tiltmeters in Italy. This dataset provides one of the few direct comparisons of amplitudes for both events recorded on common instruments, and the authors find that Sumatra–Andaman spectral amplitudes are, in general, smaller than those for the 1960 Chile event by a factor between 1.5 and 3.

For many earthquakes, estimates of radiated energy can be difficult to make. For the 2004 Sumatra–Andaman earthquake, the long duration and overlap of interfering arrivals in the commonly used calculation window make the task especially difficult. Because the duration of the P wave is long enough to include later arrivals, some standard methods for energy calculations will fail to produce an accurate estimate. Choy and Boatwright (2007) demonstrate that an extension of the empirical Green's function method can be used to estimate the radiated energy for a great earthquake such as this one. The authors correct for the later-phase arrivals by using a modified empirical approach that produces a value of radiated energy (E_s) of 1.4×10^{17} J. Comparisons of the corrected source spectra of various analysis window durations also suggest that the second half of the rupture radiated less high-frequency energy than the first half of the rupture.

Seismicity Catalogs

Several studies in this issue describe smaller-magnitude regional seismicity that occurred both before and following the 2004 event. High-quality relocation methods are employed to refine the global catalogs, and the resulting seismicity patterns will likely be interpreted for many years to come.

Dewey *et al.* (2007) present the USGS/NEIC seismicity catalog and ancillary data for the events following the 2004 Sumatra–Andaman earthquake. The catalog includes hypocenters, magnitudes, moment tensors, radiated energy, and apparent stress values routinely calculated for regional earthquakes during the 36 weeks following December 2004. They also interpret subsets of the catalog, such as the lack of moderate-magnitude aftershocks on the deeper portion of the seismogenic thrust fault as possibly related to the complete elastic strain release during the 2004 event. In contrast, their catalog contains numerous interplate thrust aftershocks along the 2005 Nias earthquake rupture zone, possibly reflecting a difference in strain release between these two closely spaced events.

Engdahl *et al.* (2007) present locations for earthquakes in the Sumatra–Andaman region between 1918 and 2005 that have been relocated using the Engdahl–Hilst–Buland (EHB) technique (Engdahl *et al.*, 1998). The smaller depth uncertainties in this dataset are a key improvement over previous work and provide an opportunity for tectonic interpretations. For instance, the authors use this dataset to show a sharp separation between aftershocks of the 2004 and 2005 great earthquakes as well as variations in the slab dip and downdip seismogenic width along strike in the subduction zone.

Bilek (2007) examines several tens of $M_w > 6$ earthquakes that occurred between 1992 and 2005 along the Sumatra–Andaman subduction zone to find that shallower events have longer durations, similar to other subduction zones in the circum-Pacific. Along-strike variation does not show a slow character in the Nicobar and Andaman segments; hence, the possible slow rupture in these segments during the 2004 mainshock is not interpreted to be caused by frictional variations along strike in the subduction zone. Absence of temporal change in the depth dependence before and after the 2004 earthquake suggests that the rupturing process in 2004 did not alter the fault-zone frictional conditions either.

Mishra *et al.* (2007) describe aftershock locations determined by using data from a temporary network of six three-component short-period seismometers deployed on the Andaman and Nicobar Islands following the 26 December 2004 Sumatra–Andaman earthquake. The network recorded ~18,000 aftershocks, and the authors present earthquake statistics such as average b -value (0.77) for this dataset. Patterns in the aftershock locations are also compared with regional tectonic features.

Spatial and Temporal Rupture Characteristics

Banerjee *et al.* (2007) compile a large dataset of Global Positioning System (GPS) static offsets to produce a slip distribution for the 2004 earthquake that reveals segmented slip along the Andaman segment, with up to 15 m of slip on its southernmost portion. They also compare estimates of geodetic and seismic moment, an important comparison as early reports of these values noted large discrepancies and led some to consider slow or aseismic slip at long periods as the cause. Based on their slip distribution, they find a coseismic geodetic moment of 7.62×10^{22} N m (M_w 9.22), only slightly larger than previous estimates of the seismic moment (6.5×10^{22} N m, M_w 9.17; Ammon *et al.*, 2005).

Vallée (2007) provides an analysis of the 2004 Sumatra–Andaman earthquake rupture using the empirical Green's function method, more commonly used for smaller-magnitude earthquakes. He demonstrates the usefulness of this technique for an earthquake of this size, even using an empirical Green's function event that was significantly smaller at an M_w 7.2 and separated from the centroid of the 2004 earthquake by several hundred kilometers. This technique appears to be particularly useful for rapidly producing an estimate of the seismic moment for great earthquakes, as the author presents an estimate of M_0 5.1×10^{22} N m for the 2004 earthquake, a value comparable to the moment determined using more time-intensive analysis methods.

In one of the many examples of techniques combining two or more datasets, Rhie *et al.* (2007) compute slip distributions for the 2004 Sumatra–Andaman earthquake based on joint inversion of teleseismic and regional geodetic datasets. They find that values of maximum slip near 4° N and high slip through to 10° N are the key controls on the fit to the seismic data, whereas inversion of the GPS data suggests significant slip in the northern segments. The detailed sensitivity analyses presented in this article clearly show the importance of each dataset on the slip-distribution patterns, bolstering the case for using both of these complementary datasets for a more complete view of the rupture process.

Using yet another dataset, Lambotte *et al.* (2007) use a singlet-stripping technique to isolate parameters from the gravest free oscillations recorded around the globe to describe the spatiotemporal extent of the sources for both the 2004 Sumatra–Andaman and the 2005 Nias earthquakes. For the 2004 earthquake, they find a rupture length and duration of ~1250 km and 550 sec, respectively, consistent with studies using teleseismic or GPS datasets.

Ground Motions

This volume includes estimates of ground motions in the northern Sumatra region based on finite-fault modeling and recorded seismograms. Sorensen *et al.* (2007) use a multiasperity fault model over a large frequency range to calculate the expected ground motions in northwestern Sumatra and the nearby offshore islands. Their results suggest

the largest ground motions were on the order of 200 cm/sec in bedrock regions near the highest-slip regions, and less severe shaking in the Banda Aceh region of 60 cm/sec. These estimates suggest that ground shaking played an important role in destruction of some of these regions prior to the tsunami striking the area.

Coseismic and Postseismic Deformation

Combining geodetic and field observations of subsidence and emergence provide estimates of coseismic and postseismic deformation. Chlieh *et al.* (2007) incorporate regional continuous and campaign GPS measurements and coral uplift observations to describe the coseismic and postseismic deformation associated with the 2004 Sumatra–Andaman earthquake. They determine a 1500-km-long coseismic rupture with peaks in moment release at 4° N, 7° N, and 9° N and a total moment of $\sim 6.7\text{--}7.0 \times 10^{22}$ N m (M_w 9.15). The coseismic model is also used to predict sea surface heights during tsunami propagation, finding a good fit with the satellite altimetry data. In addition, the model of postseismic deformation suggests that slip continued on the interface beyond the 500-sec seismic slip, with $\sim 2.5 \times 10^{22}$ N m of postseismic geodetic moment release.

Rajendran *et al.* (2007) provide the most comprehensive evidence to date from the field for uplift and subsidence on the Nicobar and Andaman islands. They use mangrove forests, corals, and anthropogenic features to document subsidence at all visited locations on the Nicobar islands and a complex pattern of subsidence and emergence on the coasts of the Andaman islands. Their results are consistent with analysis of satellite imagery (Meltzner *et al.*, 2006), but provide additional constraints on the magnitude of the vertical deformation that are useful in modeling slip on the megathrust.

Tsunami Studies

The earthquake generated a large transoceanic tsunami that was well recorded by tide gauges, coastal run-ups, and for the first time, by orbiting satellites. These data are being used to model the tsunami source and provide comparisons with the seismic source, with new challenges and understanding coming from incorporation of the satellite altimetry.

Fujii and Satake (2007) perform one of the first joint inversions of regional tide gauge data and satellite altimetry measurements to produce a tsunami source model that extends ~ 900 km to the north along the subduction zone. They find a slip distribution, stable within a large range of rupture velocities and rise times, with peak slip of 13–25 m offshore Sumatra Island, with moderate slip of up to 7 m in the Nicobar Island region. Although there are still some discrepancies between results produced from either tide gauge or satellite data alone, this article provides detailed descriptions

of the inversion results for individual datasets as well as the joint inversion.

Hébert *et al.* (2007) present tsunami numerical simulation in the Indian Ocean with special focus on the Mascarene Islands and compared the results with tide gauge record and run-up measurements on La Réunion Island. Tsunamis computed from uniform and heterogeneous slip distributions show distinguishable differences in maximum water-height distribution on both basinwide (Indian Ocean) scale and local scale on harbors in the islands. An important conclusion is that a tsunami source off southern Sumatra, similar to the 1833 source, would produce larger tsunami impact on La Réunion than the 2004 models.

Piatanesi and Lorito (2007) invert tsunami waveforms recorded at 14 tide gauge stations around the Indian Ocean to estimate rupture velocity and the slip distribution on the fault. The largest slip is estimated to be 30 m on a deeper subfault off Aceh Province. Large slip (mean slip > 10 m) is estimated on shallow subfaults beneath Great Nicobar to Little Andaman Islands. The slip was also large, about 20 m, on a deep subfault east of North Andaman Island. The mean rupture velocity is estimated as 2.0 km/sec.

Hanson *et al.* (2007) analyze tsunami signals recorded on hydrophones and seismic stations for the 2004 and 2005 events. The tsunami signals between 1 and 30 mHz show dispersive character expected for a gravity wave in the ocean; shallow-water wave at lowest and deep-water wave at highest frequency, respectively. The high-frequency tsunami signals in December originated west off Sumatra and near Great Nicobar Island, where large slips were inferred by other studies. They also show that islands or a submarine plateau acted as reflectors for high-frequency tsunami signals.

Geist *et al.* (2007) examine various tsunami forecast models and compare the results with the observed data from the 2004 tsunami. While an empirical method based on a scalar point source can successfully forecast the mean and maximum tsunami heights, a subfault dislocation model with real-time data dissemination is needed to reproduce the observed regional variation of tsunami heights. They test a stochastic source model as a tsunami hazard-assessment model and find that small average slip (9 m) with a long fault (1600 km) best reproduce the observed run-up values.

Nawa *et al.* (2007) use a set of geophysical instruments deployed off the coast of Antarctica in their analysis of the 2004 tsunami. They model observations from an ocean-bottom pressure gauge, a superconducting gravimeter, and a broadband seismometer. Although their predictions match the amplitudes and periods of the observed data well, the timing of the model signals differ from the data.

Tectonic Comparisons

The 2004 earthquake necessitates a revisitation of commonly accepted views on the relationship between the size of great earthquakes and physical characteristics of subduc-

tion zones. Stein and Okal (2007) re-enter the debate over whether such great earthquakes occur only in regions of fast subducting young slabs. They first provide an estimate of the size of the 2004 event (M_w 9.3) using long-period normal modes. They then note that the oceanic lithosphere is old and is subducting at a low velocity. Thus, the Sumatra–Andaman earthquake violates the earlier concept of great earthquakes being confined to fast, young subduction zones. The authors suggest that the overall correlation between great earthquakes and fast, young subduction disappears with revised velocities and ages, as well as with new earthquake data. The authors propose that the duration of the great earthquake catalog is too short to assess the likelihood of great earthquake occurrence in all subduction zones.

Because of the large tsunami generated by the 2004 earthquake, there is a question as to whether the 2004 event is a “tsunami earthquake” as defined by Kanamori (1972). These earthquakes, such as the 1992 Nicaragua earthquake, typically have slow rupture within the shallowest portion of the subduction zone fault and generate larger tsunami than expected for the surface-wave magnitude. Seno and Hirata (2007) show that the 2004 earthquake had some components of a “tsunami earthquake,” especially a long duration and some moment release in the very shallow, near-trench region. They infer that the seismogenic rupture propagated north with a rupture velocity of 2.5 km/sec, but slowed to ~ 0.7 km/sec along the near-trench region. This slow rupture consisted of about a third of the total seismic moment. They estimate that the durations of fast and slower slips were, respectively, ~ 500 sec and ~ 2000 sec from seismic-moment estimates at various frequencies, and the effective slip for tsunami generation was as large as ~ 40 m near the deformation front off Sumatra.

28 March 2005 Nias–Simeulue Earthquake

Konca *et al.* (2007) describe a joint inversion of seismic and geodetic observations for the 2005 Nias–Simeulue earthquake. This event had two distinct slip patches beneath Nias and Simeulue Islands, with a gap in between that corresponds to geologic features in the forearc. Based on this joint data inversion, the authors suggest that slip does not extend the entire fault width up to the trench, and they suggest long rise times of 20 sec and an average rupture velocity of 1.5–2.5 km/sec.

Paleoseismic and Paleotsunami Evidence for Prior Events

In the months following the Sumatra–Andaman earthquake, countries affected by the earthquake and tsunami began frantic preparations for the next giant tsunami, implicitly assuming that another such event could happen again at any time. The preliminary paleoseismic and paleotsunami work of Rajendran *et al.* (2007) suggests otherwise. They report preliminary results from a variety of promising paleoseismic

and paleotsunami sites on the Andaman islands and on the coast of India that suggest such events are, in fact, quite rare; sand layers intercalated with archeological ruins on the Indian coast imply that the previous devastating tsunami there may have occurred about a thousand years ago. This would be consistent with the average interval calculated from simple division of slip on the megathrust during the 2004 earthquake by the interseismic convergent rate.

Dedication

On behalf of all of the contributors to and reviewers of this issue of the Bulletin, we dedicate this volume to the survivors of the earthquakes and tsunami, with the hope that it will become a valuable resource for understanding and mitigating the effects of future great earthquakes and tsunami.

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